Lunar Propellant Architecture: Economic Analysis

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Lunar Propellant Business Case

• In 2016-2018, United Launch Alliance, Colorado School of Mines and others evaluated the business case feasibility for lunar-derived propellant
  • Conditions were identified that could lower the cost of satellite delivery to GEO using LO$_2$/LH$_2$ acquired in LEO

• Propellant cost, price and value were evaluated at various nodes in cislunar space based on transport from the point of origin to the point of sale

• To close this business case, **1100 mT** of propellant must be produced on the Moon for **$500/kg** or less

General Business Case Assumptions

• Lunar Ice exploration campaign cost is born by governments
  • Reduces commercial risk
  • Great synergy with science
  • Great benefit to long term sustainability of government exploration programs

• 4 year development and build for ice mining and propellant production hardware
• 1 year delivery and set up on lunar surface
• 10 year operational life
Markets for Lunar Propellant

- NASA-Science
- Military Missions
- Debris Management
- Satellite Servicing & Refueling
- International Space Station
- Human Exploration
- Space Solar Power
- Self-Sustaining Colonies
Scenarios

1. Commercial only
   • Market is propellant delivered to LEO
     • Used to refuel upper stages delivering mass to GEO or other beyond LEO destination
     • Price is $3000/kg in LEO, equates to $500/kg on lunar surface
     • Demand is 1100 mT/yr

2. Commercial + NASA (w/investment)
   • Commercial demand as above
   • NASA demand is 100 mT/yr delivered on the lunar surface
     • Refuel landers
   • NASA COTS-like investment of $800M in the development of the system
Scenarios, Cont’d

3. Commercial + NASA (w/price premium)
   • Commercial demand as above
   • NASA demand is 100 mT/yr delivered on the lunar surface
     • Refuel landers
   • No NASA investment, NASA is one of many customers
   • NASA pays $10,000/kg for propellant on lunar surface

4. NASA Only (Jones FISO business case - taxpayer $)
   • High cost launch (SLS)
   • Custom ISRU plant (no industry leverage)
   • High-cost procurement, NASA Mars is only ‘customer’
   • 100x propellant cost vs. CSM commercial architecture
   • This is a primary reason for a commercial partnership
Costs of Propellant in Cislunar Space

- **GEO**
- **LEO**
- **EML1**
- **LL0**

### Cost From Earth
- **Earth**: $0.001/kg
- **LEO**: $5k
- **GTO**: $10k
- **GSO**: $15k

### Cost From the Moon (or Asteroid)
- **L1 (or Gateway)**: $11k/kg
- **Moon**: $35k/kg

**From Earth, Utilizing Beyond Earth Propellant**

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## Business Case Analysis

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Commercial Only</th>
<th>Commercial + NASA (w/invest.)</th>
<th>Commercial + NASA (prem. price)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Propellant production rate</td>
<td>1100 mT/yr</td>
<td>1200 mT/yr</td>
<td>1200 mT/yr</td>
</tr>
<tr>
<td>Unit Cost (Moon)</td>
<td>$500/kg</td>
<td>$500/kg</td>
<td>$500/kg</td>
</tr>
<tr>
<td>NASA price (Moon)</td>
<td>NA</td>
<td>$500/kg</td>
<td>$10,000/kg</td>
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<tr>
<td>HW Dev. cost</td>
<td>$820M</td>
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<tr>
<td>HW Production cost</td>
<td>$590M</td>
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<tr>
<td>Transportation cost</td>
<td>$1062M</td>
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</tr>
<tr>
<td>Annual ops &amp; maintenance cost</td>
<td>$75M</td>
<td>$82M</td>
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<tr>
<td>Annual revenue</td>
<td>$550M</td>
<td>$600M</td>
<td>$1550M</td>
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<tr>
<td>NASA cost share</td>
<td>$0M</td>
<td>$800M</td>
<td>$0M</td>
</tr>
<tr>
<td>Internal Rate of Return (IRR)</td>
<td>9.8%</td>
<td>18.3%</td>
<td>31.6%</td>
</tr>
</tbody>
</table>
USG Benefit of Commercial Scenarios

• Scenario 2
  • $800M public investment (development cost offset)
  • $1.3B total cost for 10 years of propellant supply
  • $3.45B annual savings (vs propellant launch from Earth)
  • NASA price for propellant $500/kg
  • 80% IRR to NASA

• Scenario 3
  • No initial USG investment
  • NASA price for propellant is $10,000/kg
  • $10B total cost for 10 years of propellant supply
  • $2.5B annual savings (vs propellant launch from Earth)
Backup Charts
Discussion

• Public-Private Partnerships can substantially increase the returns to a commercial lunar propellant company

• Both models generate positive ROI (Scenario 2 and Scenario 3)
  • NASA can invest up front to receive a commodity price for propellant
  • Or, NASA can buy propellant at a commercial price premium
    • Substantially below cost to transport propellant from Earth,
    • But above commodity price

• NASA investment reduces up front cash well (debt) and provides early NASA commitment
  • The more early NASA investment, the lower the risk

• NASA paying a premium price will generate higher commercial returns in the long run, but carries risk of NASA reneging on the guarantee
Estimated Architecture Costs

![Bar chart showing estimated architecture costs for different subsystems.

The chart compares costs for development and build for each subsystem, with costs ranging from $0 to $250,000.

Subsystems include:
- KEUS-derived storage tanks (3)
- Purification and electrolysis plant
- Comm relay
- Cold traps (3)
- GP vehicle
- Power generation plant
- Rim mirror assembly (3)
- Haulers/tankers (3)
- Capture tent
- Secondary optics
- Ground system

The chart indicates that the power generation plant and rim mirror assembly have the highest costs, with development costs significantly higher than build costs for many subsystems.]
Mining Company Cash Flow

IRR = 31.6%

IRR = 18.3%

IRR = 9.8%
Sensitivity Analysis

• Scenario 1
  • Propellant price vs IRR
  • project cost vs IRR

• Scenario 2
  • Propellant price vs IRR
  • IRR vs NASA investment

• Scenario 3
  • IRR vs NASA price
Scenario 1, Sensitivity Analysis

- Prices are based on a LEO point of delivery
- Aerobraking can reduce the fuel consumption of deliver from the Moon to LEO by a factor of 2
  - Increases allowable price on the lunar to $1000/kg
- Cost increase of 40% still results in positive returns
Scenario 2, Sensitivity Analysis

• The PPP and aerobraking can increase returns to over 35%

• Increased NASA investment dramatically increases returns
Scenario 3, Sensitivity Analysis

• Any premium paid for propellant in lunar proximity (compared to that delivered to LEO) increases returns